# Introduction to Quantum Metrology

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## Quantum Standards and Instrumentation

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# Preface

Quantum metrology is a field of theoretical and experimental study of high-resolution and high-accuracy methods for measurement of physical quantities based on quantum mechanics, particularly using quantum entanglement. Without equivalent in classical mechanics, quantum entanglement of particles or other quantum systems is an unusual phenomenon in which the state of a system can be determined better than the state of its parts. Attempts are made to use new measurement strategies and physical systems in order to attain measurement accuracy never achieved so far.

Quantum metrology sprang into existence at the beginning of the twentieth century, along with quantum mechanics. After all, the Heisenberg uncertainty principle, together with the Schrödinger equation and the Pauli exclusion principle constituting the basis of the formalism of quantum mechanics, is also the fundamental equation of quantum metrology. The uncertainty principle sets limits to measurement accuracy, but has no relation to the technical realization of the measurement.

Quantum metrology only started to develop in the latter half of the twentieth century, following the discovery of phenomena of fundamental importance to this field, such as the Josephson effect, the quantum Hall effect or the tunneling of elementary particles (electrons, Cooper pairs) through a potential barrier. Using new important physical advances, quantum metrology also contributes to progress in physics. In the past 50 years the Nobel Prize was awarded for 16 achievements strongly related to quantum metrology. In 1964 Townes, Basov and Prokhorov received the Nobel Prize *for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle*. Presently masers constitute a group of atomic clocks, installed in metrology laboratories as well as on satellites of GPS and GLONASS navigation systems. Gas lasers are basic instruments in interferometers used in metrology of length, and semiconductor lasers are used in industrial measurements. Haroche and Wineland were awarded the Nobel Prize in 2012 *for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems*, that is, for studies in the field of quantum metrology. In 1964–2012 the Nobel Prize was awarded for important discoveries such as *the Josephson effect* (Josephson

1973), *the quantum Hall effect* (von Klitzing 1985), and *the scanning tunneling microscope* (Röhrer and Binnig 1986). Thus, scientific achievements in quantum metrology or relevant to this field are considered very important for science in general.

Currently, the major field of practical application of quantum metrology is the development of standards of measurement units based on quantum effects. Quantum standards are globally available universal primary standards that allow to realize a given unit at any place on the Earth by measurements which, in appropriate conditions, will yield equal results anywhere. The creation of quantum standards of the base units of the International System (SI) is in accordance with the objectives set by the International Committee for Weights and Measures and realized in collaboration with the International Bureau of Weights and Measures (BIPM).

This book provides a description of selected phenomena, standards, and quantum devices most widely used in metrology laboratories, in scientific research, and in practice.

The book opens with a discussion of the theoretical grounds of quantum metrology, including the limitations of the measurement accuracy implied by theoretical physics, namely the Heisenberg uncertainty principle and the existence of energy resolution limits, discussed in Chap. 1. Providing the rudiments of systems of measurements, Chap. 2 discusses the currently adopted standards for the realization of SI units, and the changes in the classical system of units allowed by quantum metrology. Chapter 3 is devoted to the activities and proposals aimed at the development of a new system of units to replace the SI system, with units of measurement defined in relation to fundamental physical and atomic constants. Chapters 4, 6, 9, 10, and 12 present the theory and practical realizations of quantum standards of units of various quantities: the voltage standard using the Josephson effect, the resistance standard based on the quantum Hall effect, the atomic clock-based frequency standard, the length standard using laser interferometry, and the mass standard based on the masses of atoms and particles. Chapter 11 is devoted to scanning probe microscopy. Chapters 5 and 8 discuss sensitive electronic components and sensors based on quantum effects and including, among others, superconducting quantum interference magnetometers (SQUIDs), single electron tunneling transistors (SETT), and advanced quantum voltage-to-frequency converters based on the Josephson junction. Presented in Chap. 5 along with many application systems, SQUIDs are *the most sensitive of all sensors of all physical quantities*.

The description of the discussed devices and the underlying physical effects is complemented by a presentation of standardization methods and principles of comparison between quantum standards (with the time standard used as an example) in accordance with the hierarchy of the system of units.

Intended to serve as a textbook, this book also represents an up-to-date and hopefully inspiring monograph, which contributes to scientific progress. As a scientific survey it puts in order the fundamental problems related to electrical metrology, the universal standards, and the standardization methods recommended by BIPM. As an academic textbook it propagates a new approach to metrology, with more emphasis laid on its connection with physics, which is of much importance for the constantly developing technologies, particularly nanotechnology.

Large parts of this publication represent a translation from my book *Introduction to Quantum Metrology* published in Polish by Publishing House of Poznan University of Technology in 2007 and used here in translation with the publisher's permission.

I thank all those who helped me collect material for this book. Special thanks go to my colleagues at the Polish Central Office of Measures in Warsaw and at Physikalisch-Technische Bundesanschtalt in Braunschweig.

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